Alignment in hadronic interactions

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Abstract

The alignment of the products of very high energy interactions seen in mountain altitude experiments is one of the most puzzling phenomena in cosmic ray physics for quite a long time. The observations of the Pamir and Chacaltaya emulsion chamber groups and by the Tien-Shan extensive air shower experiment, together with a very clear event seen in the Concorde French–Japanese experiment in the stratosphere, makes the experimental basis very substantial. In the present paper a novel possible explanation is put forward. 13.85Tp, 13.87.Fh

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I. INTRODUCTION

The Pamir experiment comprises an X-ray film chamber which contains events with genuinely correlated dark spots produced by very energetic cosmic ray shower particles distributed implausibly asymmetrically [1]. This effect, called "alignment" occurs, according to Ref. [2], at a primary particle energy of 8×10^{15}eV above which the rate increases rapidly with interaction energy. For the energies of interest the cosmic ray flux is very low, so the statistics in the Pamir experiment are very limited; specifically only 62 events of visible electromagnetic energy in the range from 700 to 2000 TeV. Problems with the statistics and the quite complicated methodology of the large area X-ray film calorimeter make the measurements very difficult. Thus, independent confirmations by the Chacaltaya group [3], the Tien-Shan extensive air shower experiment [4], and the one event of high quality recorded in the Concorde French-Japanese experiment [5], are indispensable. All this implies rather strongly that there is the azimuthal asymmetry of particle production at energies above about 10^{16}eV.

Some explanations exist in the literature already. The most conservative one is the fluctuation explanation by J.N. Capdevielle [6]. Calculations show that with conventional fluctuations of the elementary act the probability of producing the Concorde event could exceeded the "5σ" level, the commonly accepted limit for a "new physics" discovery. However, the increase of the fraction of aligned events to $(27\pm0.09)\%$ at the highest energies seen, makes this explanation less probable [2]. Even if it could be responsible for the one stratospheric event, which is, in fact, slightly different than the rest of "X-ray aligned" events, taken all together a different solution is required.

The rotating nuclei fragmentation hypothesis of Erlykin and Wolfendale [7] is naturally connected with the postulated increase of the fraction of heavy nuclei in the primary cosmic ray flux around 10^{16}eV (up to 50%). However, due to the existence of the few TeV threshold in the X-ray film technique, the experiments noticeably favour primaries of higher energy per nucleon (for the same energy per particle). and the existence of heavy nuclei alone is

not enough to account for the 30% alignment that is needed. The problem was discussed in detail in Ref. [7]. The mechanism of delayed fragmentation of fast rotating nuclei need to be established theoretically as well as the possibility of a reduction of its cross section for interaction with air nuclei.

Additionally, the observation that aligned events are more abundant in the vertical component, supports the concept that the origin of the phenomenon is a deeply penetrating cosmic ray particle (most likely a proton).

The original explanations by the Pamir group [8] is supported by extensive calculations made by Mukhamedshin. He shows that the Pamir data required a significant change of the particle production act. Particle creation with a few GeV transverse momentum in a one plane cascade-like process is needed but even this is not enough to explain the data. Perhaps there is, additionally, a heavy, long lived and relatively weak interacting particle? Some theoretical ideas of the "new physics" were discussed in, e.g., Ref. [9].

II. THE PROPOSED CONCEPT OF ALIGNMENT IN THE HADRONIZATION MECHANISM

The inelastic collision of two elementary particles is conventionally treated as a scattering of particle constituents, i.e. partons, associated with the creation of excited, intermediate objects (jets, strings, chains, or fireballs), followed by their hadronization. Such a picture is confirmed by Bose-Einstein correlation studies, where the time and spatial extensions of the newly created particle source is seen and measured. Both the collision and excitation processes can not be fully and quantitatively described by QCD. Specifically the hadronization is, by definition, a low momentum transfer phenomenon and at present it can be taken into account only using models. Most of the effects seen in cosmic ray interaction physics are low p_t effects. Alignment seems to be an exception, but it will be shown later that it is probably not.

It is well known that the scattering can be described in the impact parameter represen-

tation. This point is used to maintain unitarity by the eikonal formalism, both by the dual parton [10] and by relativistic string [11] models. For our objective, however, the details are not crucial. Differences between particular model realizations such as, for example parton scattering cross sections (at given impact parameter b) or the character of the intermediate object created, do not change the essence of the concept of this paper, and they will not be discussed here. The implications of the impact parameter picture considered strictly are valid for most of the models of multiparticle production.

The important characteristic of the string (this name will be used hereafter to label the intermediate excited objects in spite of their fireball, chain, or jet nature) is its mass. It is certainly proportional to the interaction energy [available in the center of mass system (c.m.s.) – $\sqrt{s}$], but it could also depend on other collision parameters such as the impact parameter b.

On the other hand, the string mass could be the random variable and it could fluctuate from collision to collision according to the respective probability distribution. The most familiar way of considering the chain mass behaviour is to use the parton distribution functions $F(x, Q^2)$ which describe the probability density of the colliding parton for a fraction x of the total hadron momentum (Q^2 defines the scale). The particular shape of F (with its s dependence) could not be obtained from QCD. However, recent progress in lepton scattering at HERA have expanded our experimental knowledge of F significantly [12].

If we denote by b the impact parameter of the inelastic collision of two hadrons (protons) and by M the masses of two strings created (for simplicity we can take the masses to be equal, but this is not necessary) then, due to the conservation laws, the strings carry an angular momentum of

$$J_3 \approx bc \sqrt{s} \left(\frac{M}{\sqrt{s}} \right)^2 . \tag{1}$$

Here, M is, to be precise, the energy of the (rotating) string in its c.m.s.. It is of the same order as the energy (mass) of the string in the co-rotating frame.

The angular momentum of the string is related to its (end) rotation velocity, ω. In the

case of particular model of the string (Nambu-Goto-Polyakov, NGP) [13], which will be used later as a numerical example, it is given by

$$J_3 \;=\; \frac{a\,R}{2\,\omega}\left[\,\frac{\arcsin\left(\omega\,R/c\right)}{\omega\,R/c} \;-\; \sqrt{1\;-\;\left(\frac{\omega\,R}{c}\right)^2}\,\right] \;\approx\; \frac{M\,c^2}{2\,\omega}\;. \tag{2}$$

Comparing Eqs.(1) and (2), the angular velocity of the relativistic string is of the order of

$$\omega \;\approx\; \frac{c}{b}\,\frac{\sqrt{s}}{M}\;. \tag{3}$$

The above relations certainly does not hold for central collisions, and also in all other cases it should be treated rather approximately, just to illustrate the importance of relativistic rotation of fragmenting strings.

III. THE ANGULAR MOMENTUM PROBLEM OF STRING FRAGMENTATION.

If we have a (rotating) string of mass M, the next step to be considered is its fragmentation. The commonly used hadronization models can be cluster type-like (HERWIG [14]) or string fragmentation-like (LUND [15]). Nevertheless, both deal with a one-dimensional coloured field structure, and this one-dimensionality is an important part of the models. The LUND picture possesses a well described space–time particle production scheme. It is shown in Fig. 1. Details and particular model parameter values are adjusted to the measurements. The recent and most accurate tests of hadronization models are made with the precise data on the Z^0 energy from LEP [16]. The important point is that just as in the case of e^+e^- annihilation the linear structure of the Z^0 decay created chain is (can be) very well justified due to the vanishing of the string angular momentum. The fact that the same procedures can be used for hadronization of fast rotating strings from hadronic inelastic collisions is rather astonishing. However, a closer look at particular Monte Carlo realizations exhibits many modifications which make the previous amazement less surprising.

The problem with the angular momentum, or rather the lack of it, seems to have a very long history. The famous Fermi [17] statistical model was published just fifty years ago. It is interesting that the importance of the problem was clear to Fermi. He described the exact way of avoid it by using the impact parameter formalism. He even made some calculations, concluding that *"It was found in most cases that the results so obtained differ only by small numerical factors from those obtained by neglecting the conservation of angular momentum. This has been done as a rule in order to simplify the mathematics."* This is not very surprising taking into account the low energies which Fermi had to deal with (in the main part of his paper); these were of the order of hundreds of MeV to a GeV or so. However, an interesting remark can be found in the second last page where he discussed the *"collisions of extremely high energy"* ($10^{12 \div 13}$eV). He found that the conservation of angular momentum reduces the produced pion multiplicity, and also *"...has the effect that the angular distributions of particles produced is no longer isotropical...".*

Ten years after Fermi's paper, when it become clear that the products of high energy collisions are strongly collimated along the interaction axis, Hagedorn published paper [18] concerning the statistical treatment of the *not-so-isotropic* angular (in c.m.s.) distribution of collision products. In this paper interesting statements appeared: *"This whole question* [the angular momentum conservation problem]*, though of practical importance, seems to be still not understood. At least angular momentum conservation does not play an important quantitative role. ... So at present it seems most reasonable to disregard angular momentum at all,...".* Although the model discussed in the mentioned paper was assigned for central collisions, everything was entirely correct. The problem of the most frequent, peripheral collisions, however, remains. Hagedorn himself, again ten years later, gave the solution in his paper called "The Thermodynamical Model" [19]. The solution was transient rather than fundamental. He introduced *the velocity weight functions* which describes a part of strong interaction physics (unknown from first principles) and *"To this one should add over-all conservation of angular momentum"*. And this temporary solution survived thirty years! It can be found in more or less sophisticated transcription in many contemporary string

hadronization models.

Coming back to the LUND hadronization and its space–time structure shown in Fig. 1, an important remark has to be made concerning the time sequence of the chain breakups. The dashed hyperbolic curve in the figure represents the string point of the same proper time in their local co-moving frames. This can be associated with the hadronization time of the string, but, as is seen, in the string center of mass system hadrons occur at different times. It is clear in Fig. 1 that the slowest hadrons appear first, while those with high velocities (in the string c.m.s.), especially those containing initial string creating partons, materialize last. This somehow puzzling statement has, in fact, been known from the very beginning of relativistic string theory (see e.g., Refs. [20]). For the relatively low energy collisions with only a few particles created it may cause problems [21]. To be precise, one has to note that, of course, in some cases, due to the random nature of the process (which is slightly more complicated than that which is shown in the discussed simple graph), some exceptions can be expected.

The main point is that the central part of the string fragments after some "freeze-out" time (about 1 fm/c) and the very end needs longer time (in the string c.m.s.) and we can expect that the rotation speed could be large enough to bend the particle production direction away from the interaction axis in the intervening time. Of course all particles in between will tend to lie on the one plane defined by the impact parameter vector and in this way the particles created are apparently aligned in the laboratory frame of reference. What should be noticed here is that the production of particles with relatively high transverse momentum (with respect to the interaction axis) is not due to any special high momentum transfer process (new physics) but is simple a result of kinematic with the usual non-perturbative hadronization.

IV. THE CURVED STRING FRAGMENTATION.

The consequences of the string rotation presented above could, however, be quite wrong, because of the well known fact of the non-existence of "rigid" rotation in highly relativistic system. The one dimensional fragmentation structure of the LUND model should be extended making the problem definitely much more complex when we deal with a fast rotating QCD string.

The main question here is the shape of the string. Detailed calculations (see, e.g., Ref. [13]) assuming a particular model of action for the string system show that there are some deviations from the straight string shape. In Fig. 2 the solution is presented. The measure of the curvature of the string is in this case proportional to the, e.g., rate of longitudinal expansion, so the vertical scale in the figure is in this sense arbitrary. The solution was obtained (in an analytical form) assuming small string deflections by perturbation of the straight string solution, thus, dropping some terms in the general string evolution equation, which do not have to be necessarily small in our case. The lack of an exact solution makes further examination somehow uncertain, but we do expect that the general behaviour of the real string shape is similar to the one shown in Fig. 2.

The main difference between the straight rotating string and the "real" (Fig. 2) string is that the end quark of the string (leading one) still moves almost along the interaction axis direction while the inner part of the string bends.

The problem of hadronization and specially its space-time structure (similar to the one presented in the Fig. 1), of the curved string is, in general, unsolved. Inertial forces acting along the string could have an effect on the string area law thereby changing the string "decay" constant. Additionally, the problem of clock synchronization becomes non-trivial for rotating frames. Thus, if we can expected that the rotating string should decay *later* the meaning of the word *later*, is not entirely and indisputably defined. This makes our further analysis more uncertain, but nevertheless we will try to obtain some qualitative results.

The time evolution of the curved NGP string (such as that shown in Fig. 2) can be

simply described by the symmetrical expansion in both x and y directions as the string length grows. If, at some instant, the string begins to break (starting from its central part) the created particles will conserve the expansion speed of the particular piece of the string. From the figure it is straightforward that some of the particles created at the beginning will follow the same direction given by the string deviation. The momentum transverse to the interaction axis of subsequent particles will be getting larger (it is proportional to their longitudinal momentum) up to the moment when the fragmentation of the curved part of the string begin. Further emission angles will be smaller and smaller and in the end the rest of the created particles will follow the leading quark direction.

The relatively slow growth of multiplicity (a power-law in s with the power index of 0.3 to 0.1 or quadratic in logarithm of s] leads to the specific scaling of the arrangement of particle creation points on the curved string with the interaction energy.

As has been mentioned, the central part of the string gives, in the laboratory system, one collimated jet. It, together with the very forward produced particles forming another jet, leads to the clear binocular event reported in Ref. [22] by the Chacaltaya experiment. The central and the forward jets are formed by many constituting hadrons, thus they carry enough energy (and particles) to be visible in the X-ray chamber as two core events at energies smaller than these of the alignment phenomenon. As the energy increases, the number of particles in the central part of the string, as well as in its forward end, grows. When it is high enough, some particles appear at the transitional angles. Certainly not only the probability of production of a few high energy particles at angles in between increases, but also their energies grow, making them less sensitive to the cascading processes in the later cascade development in the atmosphere. Further calculation are needed in order to settle the details but the fast rise of the rate of aligned events seams plausible taking into account the common character of curving the relativistically rotating string.

Additionally, it is worthwhile mentioning that the discussed mechanism leaves the question of the correlation of energies and the positions of the observed energetic cores open. The general absence of any clear correlation in experimental data is difficult to explain by

other models of alignment.

V. SUMMARY.

We have proposed a mechanism which can be responsible for the alignment of the very high energy interaction product observed in high altitude cosmic ray experiments.

We postulate no "new physics". The unusual alignment of the creation processwhich had previously been suggested as extraordinary high momentum transfer processes or new, exotic particles, could be strictly kinematical effect due to the conservation laws. The conservation of the angular momentum in the creation of fast rotating strings leads to its co-planar decay. The problem of quantitative description of the hadronization of such object needs detailed knowledge of the nature of the string – chain, fireball or jet. Each of these words has its individual connotation and it has not yet been decided which (if any) describes the high energy particle production process.

The qualitative description of the relativistic rotating string could help to explain the phenomena of binocular and aligned events seen in some cosmic ray experiments.

ACKNOWLEDGMENTS

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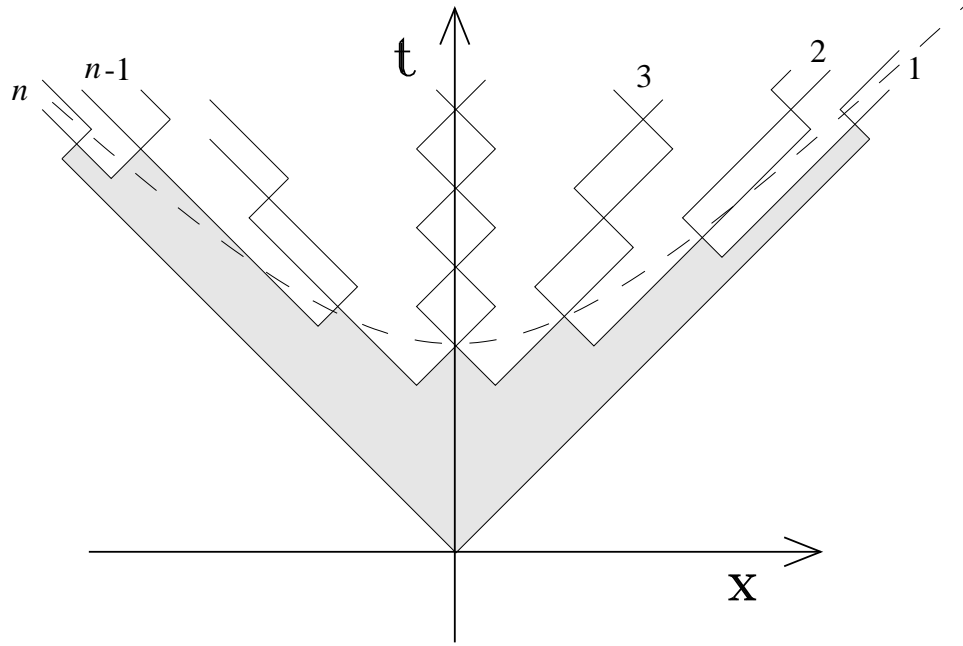
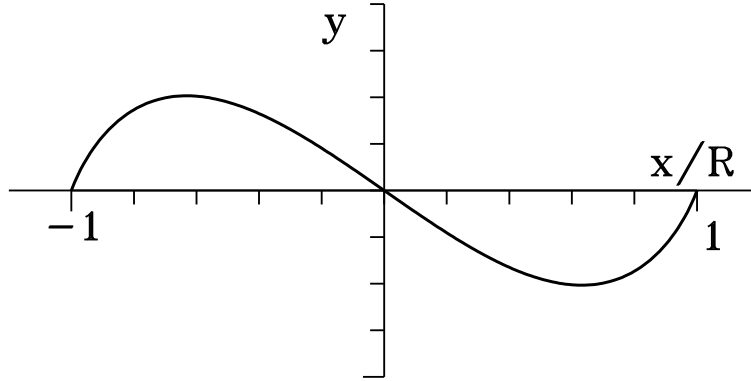FIG. 1.   Space-time structure of the relativistic string fragmentation model.

FIG. 2.   The shape of relativistic Nambu-Goto-Polyakov string. The scale of distortion is arbitrary (see text).